



Enhancing interfacial electric field in WO₃-C₃N₄ through fermi level modulation for electrocatalytic nitrogen reduction

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ABSTRACT

The electrocatalytic nitrogen reduction reaction (ENRR) has been identified as a promising method for environmentally friendly NH₃ production under ambient conditions. The interfacial electric field has been found to hold significant potential for enhancing ENRR performance. The as-prepared WO₃-C₃N₄-R catalyst exhibited a promising NH₃ yield of 43.5 μg h⁻¹ mg_{cat}⁻¹ and a high FE of 11.2 % in 0.1 M Li₂SO₄. DFT calculations indicate that the enlarged Fermi level can induce more electrons transfer from WO₃ to C₃N₄ to form a strong interfacial electric field. *In situ* Raman and FTIR spectra demonstrate that the engineered intensified interfacial electric field in WO₃-C₃N₄-R can enhance the adsorption of N₂ molecules by forming strong W-N bonds and the polarization of N≡N bond through an "acceptance-donation" mechanism, resulting in a promoted ENRR kinetics. This work demonstrates a novel strategy to design NERR catalysts and provides insights into the effects of interfacial electric field on NERR.

1. Introduction

Ammonia (NH₃) is a crucial chemical feedstock and energy carrier for the agricultural and chemical industries [1–6]. However, the traditional Haber-Bosch process used to synthesize NH₃ requires high temperature and pressure conditions [7–11], leading to excessive energy consumption and carbon dioxide (CO₂) emissions [12–15]. To overcome these challenges, the electrocatalytic nitrogen reduction reaction (ENRR) has emerged as a potential "green" NH₃ production method [16–20]. Unfortunately, the efficiency of NH₃ production through ENRR is largely limited by two critical bottlenecks: nitrogen adsorption and activation at the electrocatalyst surface [21,22].

Recently, interfacial electric field, which can accumulate reactants, facilitate electron exchange between electrocatalysts and adsorbent, and regulate the thermodynamic barriers of reactions, has been extensively studied to enhance the performances of ENRR catalysts [23–26]. For instance, our previous work reported that the strong interfacial electric field in CoO-Co₃O₄ effectively boosted the adsorption and activation of N₂, resulting in a high NH₃ yield of 59.96 μg h⁻¹ mg_{cat}⁻¹ [27]. Tang et al. constructed an electric field on the h-BN surface to promote N₂

adsorption and weaken the N≡N bond [28]. One effective method for enhancing the interfacial electric field is through Fermi level modulation in a heterogeneous catalyst. The larger Fermi level gap between two semiconductor materials, the more uneven the distribution of charge in the heterojunction, leading to a stronger interfacial electric field. For example, Yue et al. enlarged Fermi level gap between BiVO₄ and CsPbBr₃, yielding an enhanced interfacial electric field to promote photocatalytic CO₂ reduction [29]. Zhang et al. utilized a bilateral interface modification method to enlarge the Fermi level gap between the surface and bottom layers, leading to a reinforced interfacial electric field that boosted separation and oriented transport of carriers inside the perovskite film [30]. Despite the promising results of Fermi level modulation in enhancing the interfacial electric field in various catalyst systems, its potential for promoting heterogeneous ENRR catalysts has been relatively underexplored.

In this work, we focused on the construction of a WO₃-C₃N₄ heterostructure and employed a strategy of tuning the O vacancy concentration in WO₃ to widen the Fermi level gap between WO₃ and C₃N₄, resulting in an intensified interfacial electric field. We discovered that increasing the O vacancy concentration in WO₃ can shift the Fermi level

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of WO_3 upwards and hence expand the Fermi level gap between WO_3 and C_3N_4 . As a result, the prepared $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ catalyst, with higher O vacancy concentration and stronger interfacial electric field, displayed an elevated NH_3 yield of $43.5 \mu\text{g h}^{-1} \text{mg}_{\text{cat}}^{-1}$ at -0.3 V vs RHE, which was significantly higher than that of the $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ catalyst with lower O vacancy concentration and weaker interfacial electric field. Zeta potential and Kelvin probe force microscopy (KPFM) were utilized to prove the intensified interfacial electric field in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ heterostructure. Additionally, in situ experiments and density functional theory (DFT) calculations affirmed that the intensified interfacial electric field provided a strong drive force to promote the adsorption and activation of N_2 molecules on the electrocatalyst surface, leading to the observed increase in NH_3 yield. This study highlights the tremendous potential of

designing efficient ENRR electrocatalysts through Fermi level modulation, thereby enhancing the interfacial electric field in the heterostructure, and reveals the underlying mechanism of enhanced ENRR by the interfacial electric field.

2. Experimental section

2.1. Preparation of electrocatalysts

In brief, WO_3 was prepared by calcination of commercial WS_2 at 800°C for 2 h in air atmosphere. Subsequently, 45 mg WO_3 was dispersed in 10 mL methanol and then 1 mL 0.1 mol L^{-1} NaBH_4 solution was added. The obtained solution was kept stirring for another 30 min.

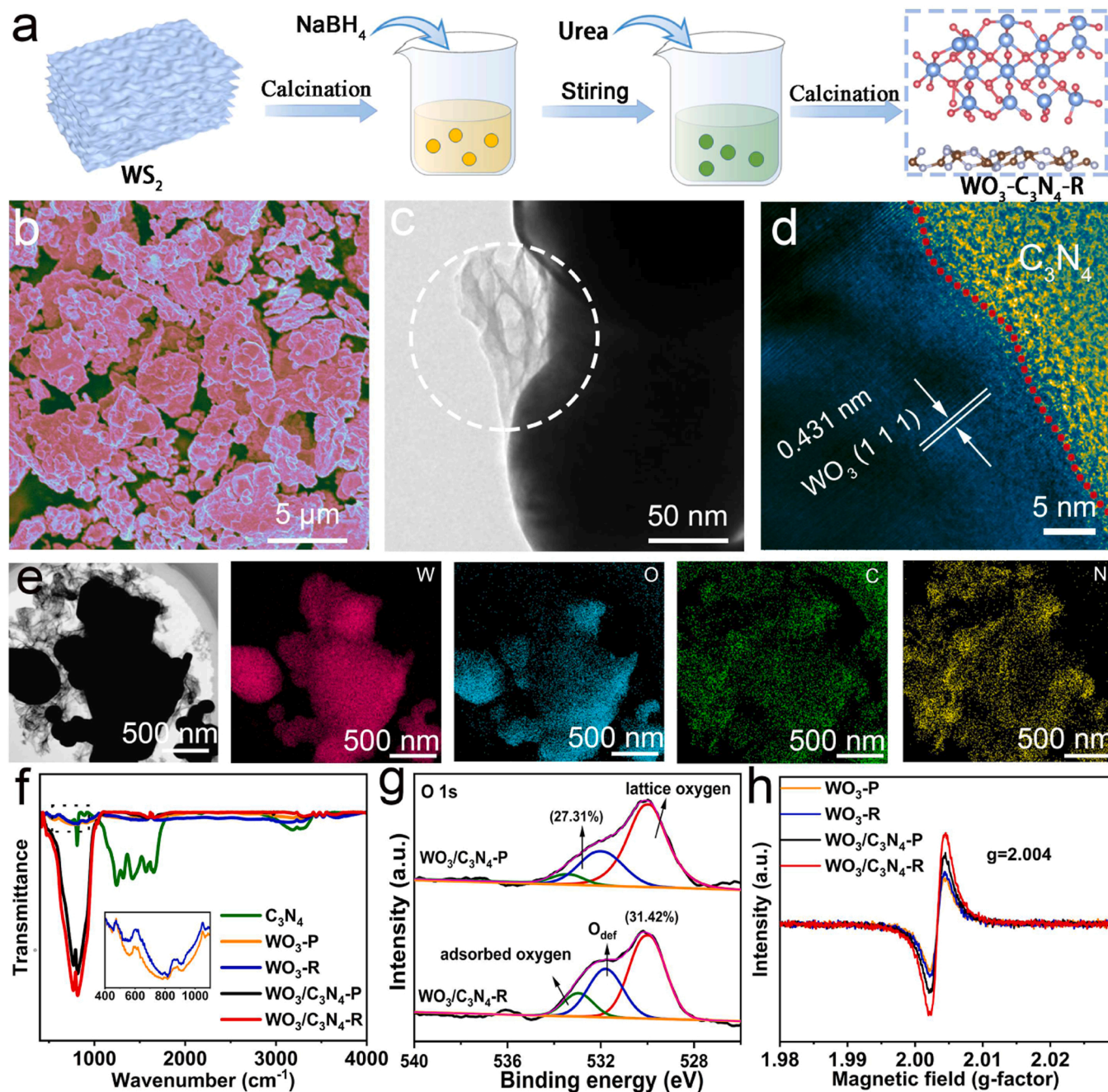


Fig. 1. (a) Schematic diagram of the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ synthesis. (b) SEM image of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$; (c) TEM image of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$; (d) HRTEM image of the selected region in (c). (e) EDS mapping results of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (f) FTIR spectra of all samples. (g) O 1s spectra of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (h) EPR spectra of $\text{WO}_3\text{-P}$, $\text{WO}_3\text{-R}$, $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$.

The excess solution was removed by vacuum filtration. The obtained products were dried at 60 °C for 24 h and named as WO₃-R. WO₃-P was prepared using the same method without the addition of NaBH₄. Subsequently, 0.1 g of WO₃-R and 0.1 g of urea were meticulously ground and mixed. This amalgamation was then relocated to a horizontal tube furnace and heated to 500 °C at a rate of 5 °C min⁻¹ under a nitrogen atmosphere and kept at 500 °C for 120 min. After cooling to ambient temperature, the WO₃-C₃N₄-R was successfully synthesized. The WO₃-C₃N₄-P samples were synthesized with the same process without NaBH₄.

2.2. Electrochemical measurements

The electrochemical N₂ reduction experiments were carried out using an H-type electrochemical reaction cell. The prepared WO₃-C₃N₄-R/CP electrode, platinum gauze electrode and Ag/AgCl electrode were used as the working electrode, counter electrode and reference electrode were, respectively. Pure N₂ was continuously injected into electrolyte during the NRR process.

2.3. Characterizations and calculations

The details for characterizations and calculations are provided in the [Supporting information](#).

3. Results and discussion

3.1. Synthesis and characterization of the samples

WO₃-C₃N₄-R heterostructure was fabricated through a facile method combining calcination and hydrothermal techniques (Fig. 1a). The same procedure was utilized to fabricate WO₃-C₃N₄-P catalysts without the addition of NaBH₄. Furthermore, WO₃-R and WO₃-P were synthesized through the calcination of WS₂ with and without NaBH₄, respectively. C₃N₄ was prepared via urea pyrolysis and liquid exfoliation [31]. The scanning electron microscopy (SEM) and transmission electron microscope (TEM) were employed to investigate the morphology of all samples. As displayed in Fig. 1b, S1 and S2a, all samples are composed of sheets without obvious difference. The TEM images demonstrate that the surface of WO₃ is adorned with C₃N₄, as depicted by the white dotted circles in Fig. 1c and S2b. The high-resolution TEM (HRTEM) images exhibit that the lattice spacing of WO₃ (111) planes in WO₃-C₃N₄-R is 0.431 nm, which is higher than that in WO₃-C₃N₄-P (0.429 nm) (Fig. 1d and S2c). It should be noted that the HRTEM images also reveal numerous and close interfacial contacts between the WO₃ and C₃N₄ components. Additionally, the elemental mapping displays a uniform distribution of W, O, C, and N elements within the WO₃-C₃N₄-R and WO₃-C₃N₄-P catalysts, as depicted in Fig. 1e and S2d. X-ray diffraction (XRD) analysis was conducted to investigate the crystal structure of WO₃-C₃N₄-P and WO₃-C₃N₄-R. As depicted in Fig. S3, the peaks at 23.1°, 24.4°, 26.6°, 34.2° and 41.9° can be attributed to the (002), (200), (202), (120) and (222) planes of WO₃ (JCPDS No. 08-0237), respectively. In addition, two characteristic peaks at 15.9° and 27.4° correspond to the (100) and (110) planes of C₃N₄ (JCPDS No. 50-1250) [32]. To further investigate the chemical bonds of the all samples, Fourier transform infrared (FTIR) analysis was performed. As observed in Fig. 1f, the spectra of WO₃-P and WO₃-R exhibit broad peaks at 450–900 cm⁻¹, which can be ascribed to the stretching vibration of W-O-W. Regarding the pure C₃N₄, the peak at 800 cm⁻¹ is assigned to the triazine vibrations, and several characteristic peaks at 1200–1600 cm⁻¹ can be related to the stretching mode of C-N and C=N heterocycles. The absorption peaks located at 3000–3500 cm⁻¹ should be assigned to the amino and surface hydroxyl groups [31]. The above results unequivocally demonstrate the successful synthesis of WO₃-C₃N₄-P and WO₃-C₃N₄-R heterostructures, and the existence of a clear interface between WO₃ and C₃N₄ components.

To further investigate the concentration of oxygen vacancies in all

samples, and X-ray photoelectron spectroscopy (XPS) and electron paramagnetic resonance (EPR) were performed. In the XPS spectra, peaks for WO₃-C₃N₄ were located at 35.73 and 37.96 eV, corresponding to W⁶⁺, while peaks at 34.81 and 37.18 eV were attributed to W⁵⁺, which was indicative of oxygen vacancies in WO₃ (Fig. S4). The peak intensity of W⁵⁺ in WO₃-C₃N₄-R was much stronger than that in WO₃-C₃N₄-P (Fig. S4), indicating that more oxygen vacancies were formed in WO₃-C₃N₄-R [33]. Further evidence can be seen in the O 1s spectrum of samples, which shows that the peaks observed at 530.01, 531.79 and 532.98 eV are attributed to lattice O species, defect oxygen and adsorbed oxygen (Fig. 1g), respectively [34]. By comparing the fitted peak area, it was found that the relative ratio of oxygen deficiency in WO₃-C₃N₄-R ($O_{\text{def}} / (O_{\text{def}} + O_{\text{lat}}) = 31.42\%$) was higher than that of WO₃-C₃N₄-P (27.31%), indicating a higher concentration of oxygen vacancies in WO₃-C₃N₄-R. Additionally, the intensity of the EPR signal was proportional to the concentration of unpaired electrons in the oxygen vacancy, and a gradual increase in signal intensity at $g = 2.004$ was observed in Fig. 1h, indicating the highest concentration of oxygen vacancies in WO₃-C₃N₄-R [35,36].

3.2. The electric field analysis of samples

To study the energy band structure of samples, UV/Vis diffuse reflectance spectra (DRS) and Mott-Schottky curves were measured (Fig. 2a and c). The band gaps (E_g) of C₃N₄, WO₃-P, and WO₃-R were calculated to be 2.56, 2.53, and 2.55 eV, respectively, using the Kubelka-Munk equation (Fig. 2b) [37]. The Mott-Schottky curves showed the flat band potentials (E_{fb}) of C₃N₄, WO₃-P, and WO₃-R were -1.12 V, -1.29 V, and -1.37 V (vs. Ag/AgCl) (Fig. 2c), respectively [38,39]. Thus, the conduction band positions of C₃N₄, WO₃-P, and WO₃-R were calculated to be -1.22 V, -1.39 V, and -1.47 V, respectively. Fig. 2d and S5 illustrate the band structures of C₃N₄, WO₃-P, and WO₃-R, where the negative shift of the CB positions indicates an upward shift of the Fermi level, leading to an increased Fermi level gap between C₃N₄ and WO₃.

The enlarged Fermi level gap between two heterostructures can enhance the interfacial electric field due the increasing difference between the electron affinity and ionization energy. Various measurements were performed to investigate the enhanced interfacial electric field in WO₃-C₃N₄-R. The ultraviolet photoelectron spectra (UPS) results revealed the work functions of C₃N₄, WO₃-P, and WO₃-R to be 9.26, 8.51, and 7.03 eV (Fig. 2e), respectively, indicating that WO₃-R is more likely to release electrons [40,41]. Zeta potential measurement was conducted to detect the surface charge with results showing that the zeta potential of WO₃-C₃N₄-R (-34.9 mV) was higher compared to that of WO₃-C₃N₄-P (-28.1 mV) (Fig. 2f) [42,43]. Moreover, KPFM was utilized to measure the surface potential of the electrocatalysts [44,45]. Fig. 2g and h show the surface potential distribution images of WO₃-C₃N₄-P and WO₃-C₃N₄-R. The corresponding line-scanning surface potential profiles indicate that the contact potential difference (CPD) of WO₃-C₃N₄-R (120 mV) was much higher than that of WO₃-C₃N₄-P (60 mV), demonstrating an intensified interfacial electric field in WO₃-C₃N₄-R. Additionally, we have quantitatively analyzed the intensity of the interfacial electric field by calculating the gradient of the fitted surface potential profiles (Fig. 2i and S6), showing that the interfacial electric field intensity of WO₃-C₃N₄-R (0.072 V μm⁻¹) was higher than that of WO₃-C₃N₄-P (0.032 V μm⁻¹). The results presented above provide compelling evidence that the enlarged Fermi level gap between WO₃ and C₃N₄ leads to an intensified interfacial electric field in the WO₃-C₃N₄-R heterostructure. This is expected to be highly advantageous for enhancing the performance of catalysts for ENRR.

3.3. Electrochemical performance

The performances of WO₃-C₃N₄-P and WO₃-C₃N₄-R for ENRR were evaluated in a typical H-type cell with 0.1 M Li₂SO₄ as the electrolyte

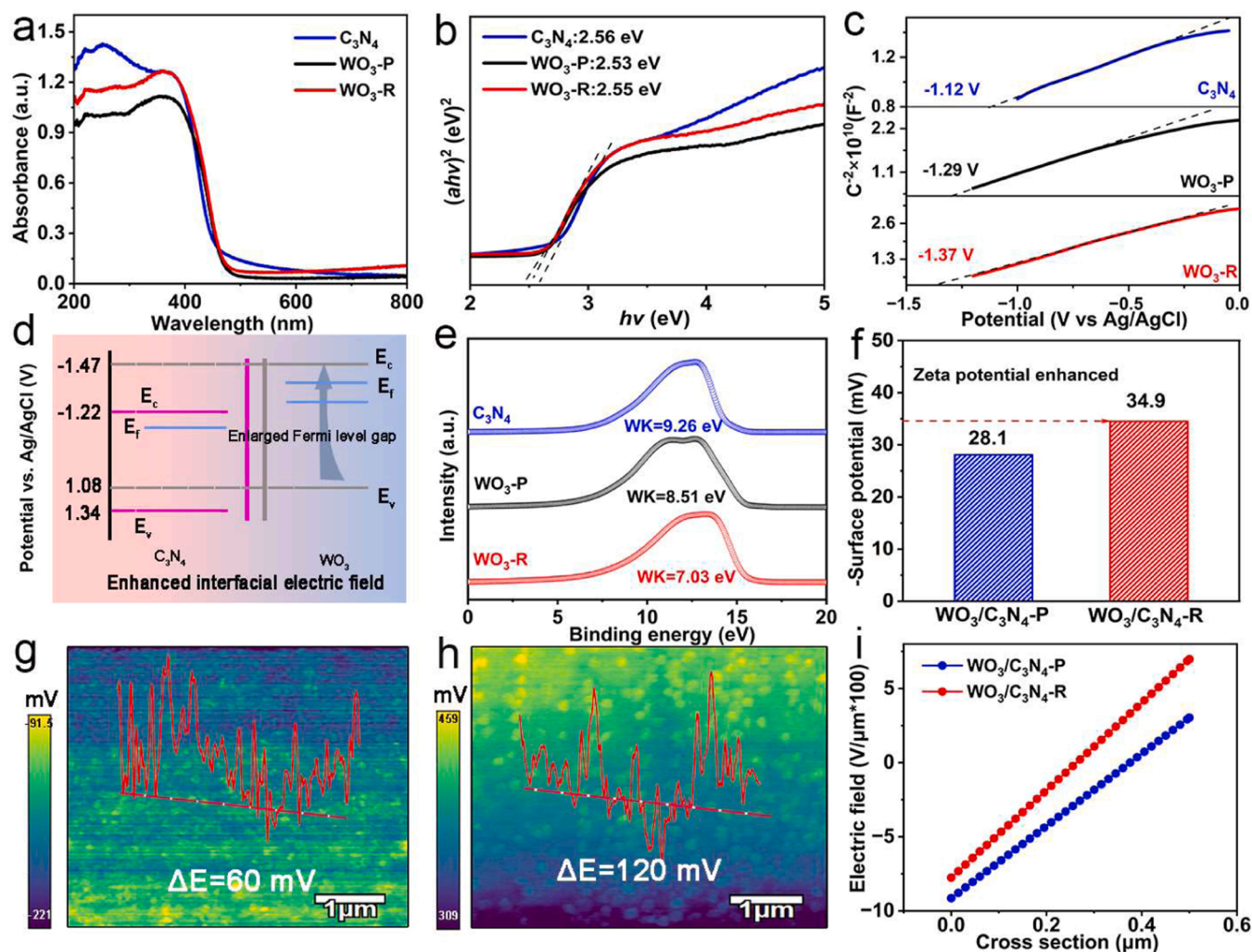


Fig. 2. (a) UV/Vis DRS and (b) Kubelka-Munk plots of C_3N_4 , $\text{WO}_3\text{-P}$ and $\text{WO}_3\text{-R}$. (c) Mott-Schottky plots of C_3N_4 , $\text{WO}_3\text{-P}$ and $\text{WO}_3\text{-R}$. (d) Illustration of the enlarged Fermi level gap between WO_3 and C_3N_4 . (e) Secondary electron cutoff edge of C_3N_4 , $\text{WO}_3\text{-P}$ and $\text{WO}_3\text{-R}$ acquired by UPS. (f) The Zeta potential of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (g-h) 2D surface potential distributions and corresponding lines scanning surface potential profiles of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (i) The intense distributions of interfacial electric field on $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ surfaces.

(Figs. S7 and S8). Initially, the N_2 gas, inclusive of the isotope gas utilized in this study, was purified. The comprehensive process detailing this procedure is available in the methods section. As substantiated by the UV-vis absorption spectra (Fig. S9), no traces of NH_3 or NO_x contaminants were detected in the purified gas. The linear sweep voltammetry (LSV) curves of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (Fig. 3a) showed a higher reduction current density in N_2 -saturated (99.99%) electrolyte than in Ar-saturated electrolyte, indicating that the catalytic reduction of N_2 to NH_3 occurred on the surface of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. Moreover, the high selectivity of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ was demonstrated as no N_2H_4 was detected (Fig. 3b and S10). The NH_3 yields were determined by UV-vis absorption spectra and the Faradaic efficiencies (FEs) were calculated according to chronoamperometry results (Figs. S11–13) [46,47]. A series of control experiments were conducted to exclude any possible interference from contaminants with results showing that no NH_3 products were detected in any of the control conditions (Fig. 3c). The NH_3 yields and FEs at applied potentials ranging from -0.1 to -0.5 V were measured and compared between the $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ electrocatalysts. As shown in Fig. 3d and e, $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ exhibited an NH_3 yield of $43.5 \mu\text{g h}^{-1} \text{mg}_{\text{cat}}^{-1}$ and FE of 11.2 % at -0.3 V vs RHE, which were significantly higher than those of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ ($38.4 \mu\text{g h}^{-1} \text{mg}_{\text{cat}}^{-1}$ and 4.2 %, respectively). Simultaneously, ion chromatograph (IC) (Fig. S14) detected the ammonia yield for the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ under

optimized condition to be $42.3 \mu\text{g h}^{-1} \text{mg}_{\text{cat}}^{-1}$, which was in close consistent with the colorimetric result ($43.5 \mu\text{g h}^{-1} \text{mg}_{\text{cat}}^{-1}$). Therefore, the IC results testified that the results by spectrophotometry is reliable. To assess the electrochemical stability of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$, consecutive recycling electrolysis was performed at -0.3 V vs RHE (Fig. 3f). The NH_3 yield and FE of the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ electrocatalyst remained almost unchanged during five consecutive cycles (each lasts two hours), implying the excellent stability of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. Furthermore, the FTIR, XRD, HRTEM and XPS were performed to verify the structure stability of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (Figs. S15 and S16). There was no discernible structural alteration of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ observed for the ENRR, signifying its commendable structural durability. In addition, the obtained performance of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ was superior to that of most recently reported ENRR electrocatalysts (Table S1). Furthermore, to investigate the source of the produced NH_3 , isotopic labeling experiments (Fig. 3g) were conducted using $^{15}\text{N}_2$ (99 atom% ^{15}N) and $^{14}\text{N}_2$ as the feeding gas. ^1H nuclear magnetic resonance (^1H NMR) spectra revealed a double coupling and a triplet coupling for $^{15}\text{NH}_4^+$ and $^{14}\text{NH}_4^+$ when using $^{15}\text{N}_2$ and $^{14}\text{N}_2$ as the feeding gas, respectively, indicating that the generated NH_3 originated from ENRR [48]. The capacitances of the samples, which were proportional to the electrochemically active surface areas (ECSAs), were determined by measuring CV curves at different scan rates (Fig. S17). The $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ sample showed a larger capacitance of

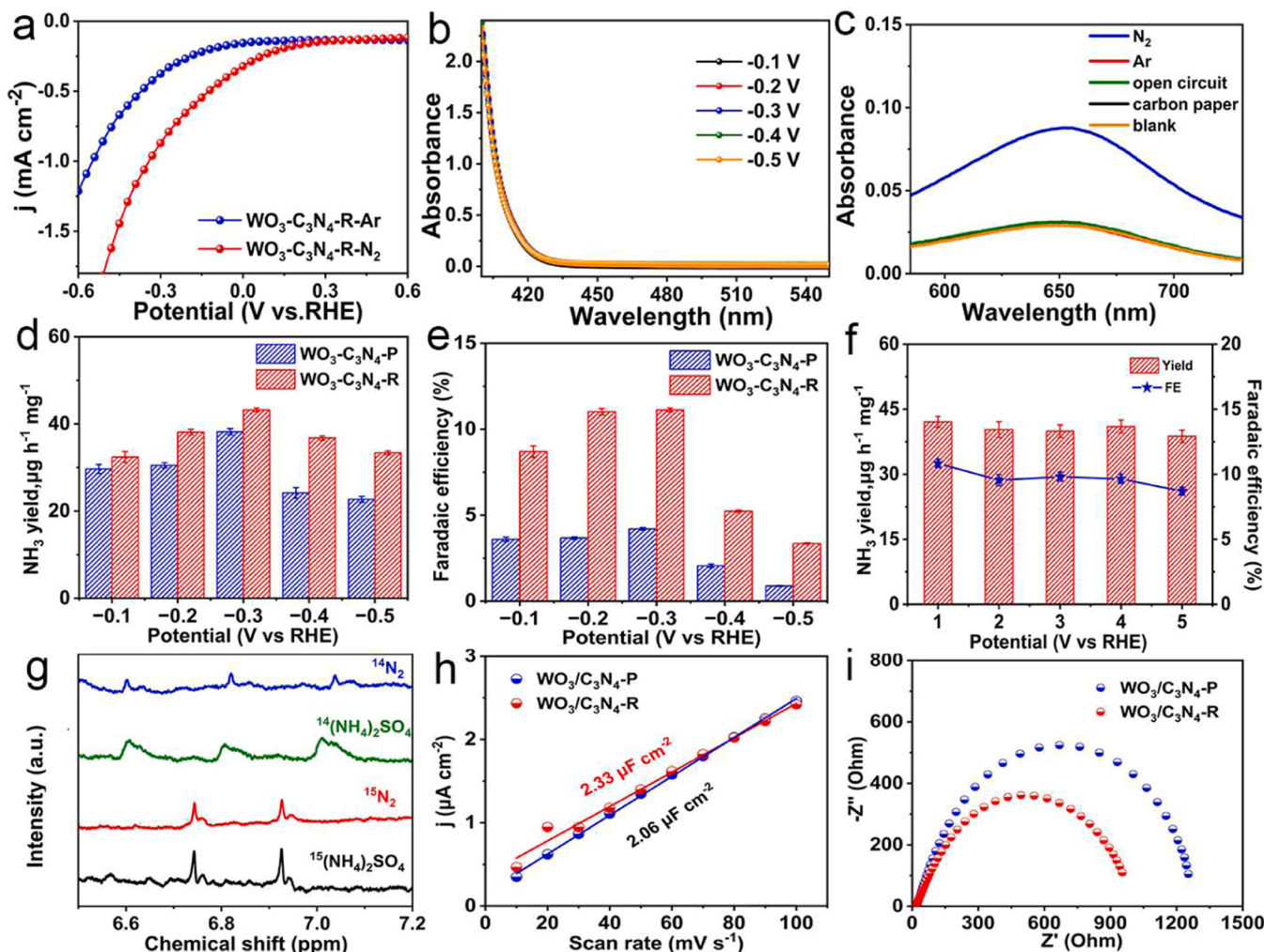


Fig. 3. (a) LSV curves of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ in Ar-saturated and N_2 -saturated 0.1 M Li_2SO_4 . (b) UV-Vis absorption spectra of the electrolytes with the Watt and Chirp's method. (c) UV-Vis absorption spectra at different control conditions. (d) NH_3 yield of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (e) Faradaic efficiency of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (f) Cycling test for $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ at -0.3 V vs. RHE. (g) ^1H NMR spectra of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ fed by $^{14}\text{N}_2$ and $^{15}\text{N}_2$ gas. (h) C_{dl} measurement of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ in 0.1 M Li_2SO_4 electrolyte. (i) Nyquist plots of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ in 0.1 M Li_2SO_4 electrolyte.

$2.33 \mu\text{F cm}^{-2}$ compared to $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ ($2.06 \mu\text{F cm}^{-2}$) (Fig. 3h) with results indicating that the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ had more active sites, which should contribute to the higher oxygen vacancy concentration in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. Besides, electrochemical impedance spectroscopy (EIS) was performed and the results showed that $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ possessed a lower R_{ct} value compared to $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$, indicating better charge transfer kinetics of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (Fig. 3i).

3.4. In situ measurements and DFT calculation

DFT calculations were further conducted to investigate the intensified interfacial electric field and charge transfer in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ heterostructure. The model $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ under different views were presented in Fig. S18. Firstly, electrostatic potential was used to illustrate the intensity of interfacial electric field in $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (Fig. 4a and d). The results indicated that the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ exhibited a larger ΔV_{et} of 13.03 eV compared to $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ of 12.23 eV, indicating a stronger interfacial electric field in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ [49,50]. Furthermore, the difference charge density was used to explore the charge transfer between WO_3 and C_3N_4 . It was observed that $2.52 e^-$ was transferred from WO_3 to C_3N_4 at the interface of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$, which was larger than $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ ($1.73 e^-$) (Fig. 4b and e). Moreover, Fig. 4c and f show the plane-averaged charge density difference of

$\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ along the z-direction [51–53]. The red and blue regions correspond to electron accumulation and depletion, respectively. It can be observed that a notable charge transfer occurs from WO_3 to C_3N_4 in both the $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ heterostructure models, which is consistent with the UPS results.

N_2 temperature-programmed desorption ($\text{N}_2\text{-TPD}$) was conducted to evaluate the N_2 adsorption behaviors of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. N_2 desorption peak of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ was observed at 565.3°C , which was notably stronger than that of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ (554.8°C) (Fig. S19). This result suggests that the intensified interfacial electric field in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ can significantly enhance the chemical adsorption of N_2 , leading to an improved ENRR kinetics [54,55]. To further investigate the N_2 -catalyst interactions, in situ Raman and FTIR measurements were conducted. The results showed a significant W-N vibrational band at 800 cm^{-1} in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (Fig. 4g), indicating that N_2 molecules were strongly adsorbed on the W metal sites. In comparison, $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ exhibited a weaker W-N vibration band (Fig. S20), indicating a weaker adsorption capacity of N_2 [56]. Additionally, the nitrogen adsorption peak exhibited a noticeable blueshift in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (1235.27 cm^{-1}) compared to $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ (1245.62 cm^{-1}) (Fig. 4h), which suggested an enlarged $\text{N}\equiv\text{N}$ bond when N_2 was adsorbed on the surface of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ [57]. Based on these observations, it can be assumed that the intensified interfacial electric field could enhance the adsorption of N_2 and activate

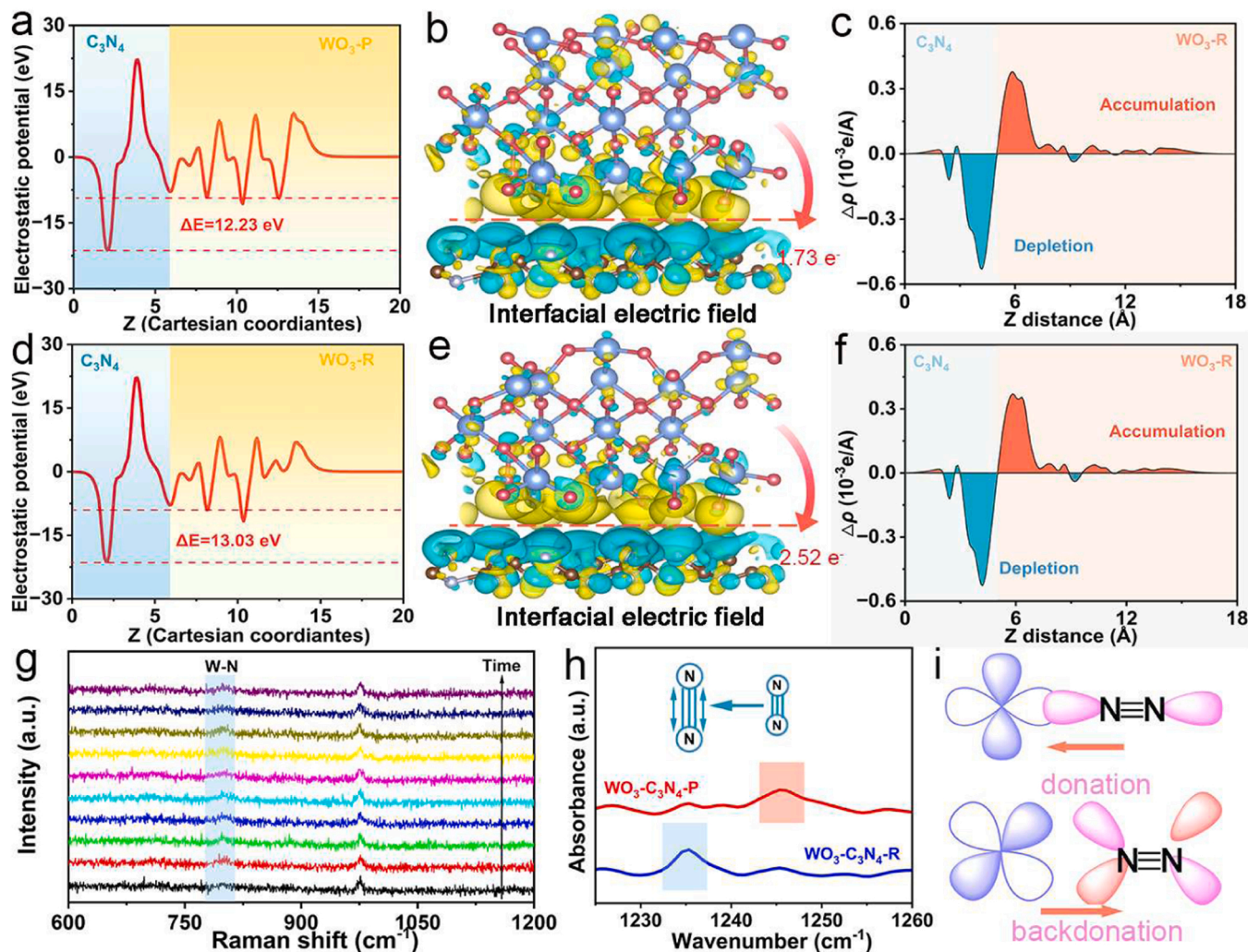


Fig. 4. (a) Electrostatic potential profile of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$. (b) The DCD of the $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$. (c) Plane-averaged charge density difference for $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ along z-direction. (d) Electrostatic potential profile of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (e) The DCD of the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (f) Plane-averaged charge density difference for $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ along z-direction. (g) *In situ* Raman spectrum of the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ at -0.3 V in $0.1 \text{ M Li}_2\text{SO}_4$. (h) *In situ* FTIR spectra of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. (i) Schematic of electron feedback mechanism from d orbitals of W to π^* of N_2 .

the $\text{N}\equiv\text{N}$ triple bond more efficiently to accelerate ENRR. Fig. 4i illustrates the "acceptance-donation" mechanism, in which the empty d orbitals of the W atom accept lone-pair electrons of the N_2 molecule. In turn, the occupied d orbital can donate electrons to the π^* orbital of N_2 , thereby weakening the $\text{N}\equiv\text{N}$ bond and activating the N_2 molecule, which facilitates its conversion into NH_3 .

To gain deeper insight into the effect of the intensified interfacial electric field on N_2 adsorption and activation, we compared the geometrical structures of N_2 adsorbed on $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$. The calculated bond lengths of W-N were 1.952 Å and 1.919 Å for $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (Fig. 5a), respectively, indicating a stronger N_2 binding affinity of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ compared to $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ [28]. In particular, the $\text{N}\equiv\text{N}$ bond lengthens to 1.154 Å and 1.157 Å after adsorption on the surfaces of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (Fig. 5a), respectively, compared to 1.10 Å in a free N_2 molecule, suggesting that the enhanced interfacial electric field in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ can effectively elongate and thus activate the $\text{N}\equiv\text{N}$ bond [58]. The distinct bond lengths of W-N and $\text{N}\equiv\text{N}$ in the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ models can be attributed to the electron transfer that occurs between the catalysts and the adsorbed N_2 molecules during ENRR. When the N_2 molecules are adsorbed onto the catalyst surface, they become polarized and form a weak bond with the catalyst atoms. This polarization induces a redistribution of electron density in the system, resulting in a transfer of

electrons from the catalyst to the adsorbed N_2 molecule. This electron transfer can lead to a weakening of the $\text{N}\equiv\text{N}$ bond. Therefore, the charge density differences were measured to investigate the electron transfer from the catalysts to the adsorbed N_2 molecules (Fig. 5b). The calculated electron transfer numbers on the $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ models are $0.902 e^-$ and $1.173 e^-$, respectively, suggesting that the intensified interfacial electric field in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ can significantly enhance the ability of the W active site to capture and activate N_2 . Based on the above results, a crystal orbital Hamilton population (COHP) analysis was further performed to investigate the high ENRR kinetics of $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ (Fig. 5c) [59–61]. The integrated COHP (ICOHP) value for the W-N bond in the $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ model was found to be -6.47 , which was larger than that of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ (-1.94). This suggests that the W-N bond in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ is stronger than that in $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$. Furthermore, the ICOHP value for the N-N bond in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ was -1.14 , which was slightly lower than that of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ (-1.15). This indicates that the intensified interfacial electric field in $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$ can significantly weaken the $\text{N}\equiv\text{N}$ bond. The NRR free-energy diagram was utilized to investigate the catalytic activity of $\text{WO}_3\text{-C}_3\text{N}_4\text{-P}$ and $\text{WO}_3\text{-C}_3\text{N}_4\text{-R}$, and the optimized configurations of intermediates are shown in Fig. 5d and S21–23. As shown in Fig. S21, the Gibbs free energy for $^*\text{NH}_2\text{-NH}_3$ to $^*\text{NH}_2$ transformation is the highest (1.853 eV), identifying it as the potential rate-determining

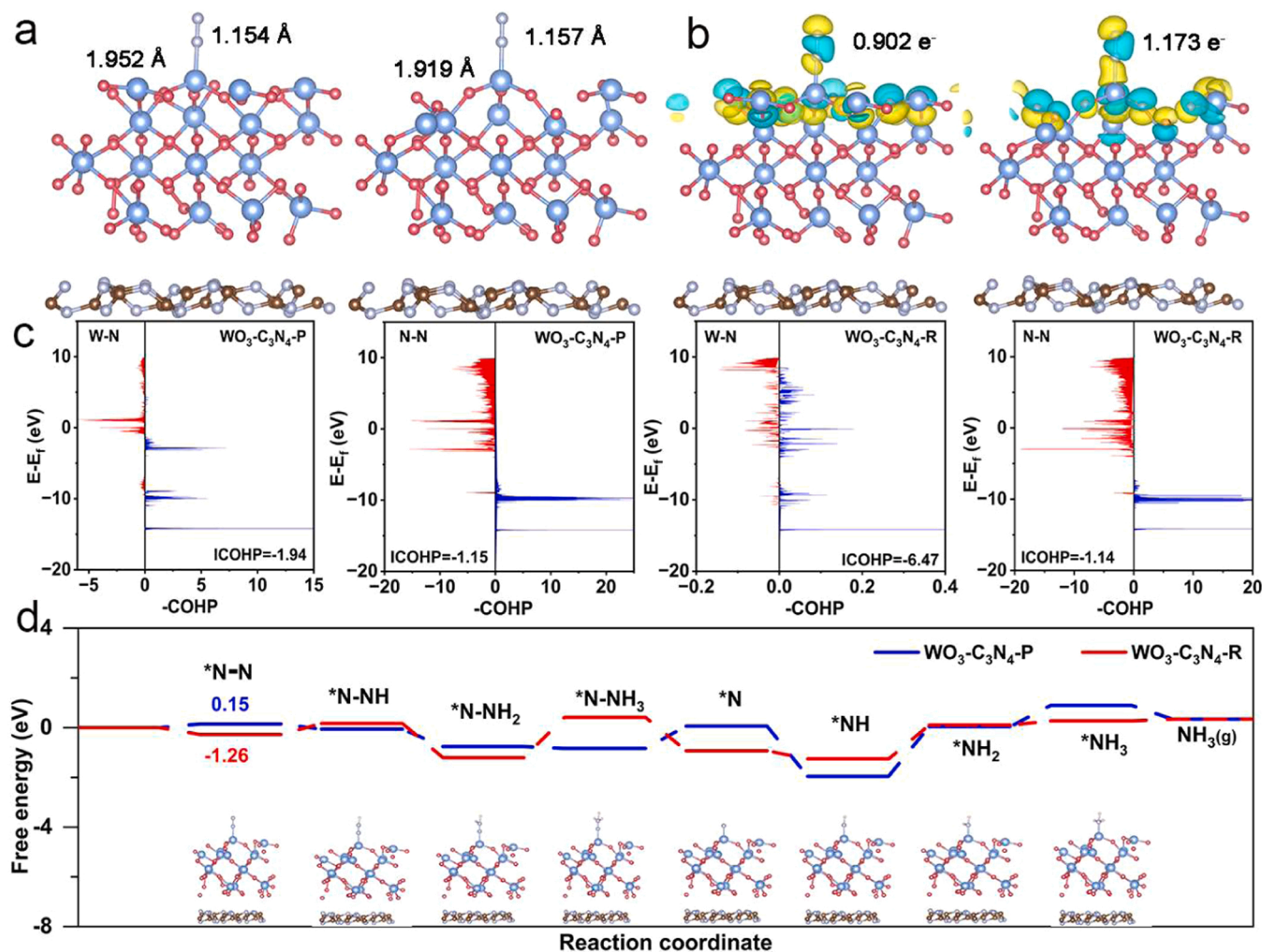


Fig. 5. (a) Optimize structures of N_2 adsorbed on $WO_3-C_3N_4-P$ (left) and $WO_3-C_3N_4-R$ (right). (b) Corresponding charge density and the electron transfer value from W to N_2 . (c) The COHP of $WO_3-C_3N_4-P$ and $WO_3-C_3N_4-R$. (d) Free energy diagram for NRR of $WO_3-C_3N_4-P$ and $WO_3-C_3N_4-R$.

step (RDS) in the alternating mechanism. For the distal mechanism, the RDS involves the conversion of $*N-NH_2$ to $*N-NH_3$, featuring a relatively lower energy barrier of 1.616 eV. Consequently, it can be deduced that the $WO_3-C_3N_4-R$ catalyst is more conducive to the distal mechanism in NRR process. Interestingly, the ENRR process on both $WO_3-C_3N_4-P$ and $WO_3-C_3N_4-R$ electrocatalysts follows the distal mechanism. The ΔG values for N_2 adsorption are -1.26 eV and 0.15 eV for $WO_3-C_3N_4-R$ and $WO_3-C_3N_4-P$, respectively, suggesting that the adsorption of N_2 on $WO_3-C_3N_4-R$ is energetically favorable, and the enhanced interfacial electric field in $WO_3-C_3N_4-R$ can optimize the free-energy barrier of N_2 adsorption. With HER serving as the principal competing reaction for the NRR, the HER behaviors of the catalysts were further examined. As shown in Fig. S24, the $WO_3-C_3N_4-R$ exhibits a higher adsorption free energy of H^+ (0.511 eV) compared to $WO_3-C_3N_4-P$ (0.344 eV), which indicates the $WO_3-C_3N_4-R$ could effectively suppress the competing HER. Overall, these computational results affirm that the $WO_3-C_3N_4-R$ electrocatalyst with intensified interfacial electric field is favor to adsorb and activate N_2 on the electrocatalyst surface, which leads to enhanced ENRR kinetics.

4. Conclusion

To summarize, enlarging Fermi level gap between WO_3 and C_3N_4 by increasing oxygen vacancy concentration in WO_3 can result in an enhanced interfacial electric field in $WO_3-C_3N_4-R$ heterostructure,

which is demonstrated as an effective strategy of accelerating the ENRR kinetics. Widen Fermi level gap enables more electrons transfer from WO_3 phase to C_3N_4 phase, resulting in an intensified interfacial electric field that providing extra driving force to capture and activate N_2 on W sites. The obtained $WO_3-C_3N_4-R$ exhibited a high electrochemical nitrogen reduction performance compared to other recently reported catalysts, achieving an excellent NH_3 yield of $43.5 \mu g h^{-1} mg_{cat}^{-1}$ and a reasonable FE of 11.2 % in 0.1 M Li_2SO_4 . This work offers a novel perspective on the modulation of Fermi level to enhance the interfacial electric field in heterostructure for efficient NERR and the insights gained from this work can be extended to the development of new catalysts in other areas.

CRediT authorship contribution statement

Xiaoxuan Wang: Writing original script, data curation, formal analysis, theoretical calculation. **Jiangzhou Xie, Shuyuan Li, Zhi Yuan, Yanfei Sun, Xueying Gao, Zheng Tang, Huiying Zhang, Jingxian Li, Shiyu Wang:** Data collection, analysis and discussion. **Zhiyu Yang, Yi-Ming Yan:** Data discussion, and draft review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.apcatb.2023.123126](https://doi.org/10.1016/j.apcatb.2023.123126).

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